December 10, 1891.

Sir WILLIAM THOMSON, D.C.L., LL.D., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

The President announced that he had appointed as Vice-Presidents—

The Treasurer.
Professor G. C. Foster.
Professor Liveing.
Sir G. G. Stokes.

The President read the following Letter from Professor Dewar:—

Royal Institution,
10*th December*, 1891.

DEAR SIR WILLIAM THOMSON,

The following observation, which I have just made, may interest the members of the Royal Society, and if you think it of sufficient importance you may announce it at this day's meeting.

At 3 P.M. this afternoon I placed a quantity of liquid oxygen in the state of rapid ebullition in air (and therefore at a temperature of $-181°$ C.) between the poles of the historic Faraday magnet, in a cup-shaped piece of rock salt (which I have found is not moistened by liquid oxygen, and therefore keeps it in the spheroidal state), and to my surprise I have witnessed the liquid oxygen, as soon as the magnet was stimulated, *suddenly leap up to the poles and remain there permanently attached until it evaporated.* To see liquid oxygen suddenly attracted by the magnet is a very beautiful confirmation of our knowledge of the properties of gaseous oxygen.

Yours faithfully,
JAMES DEWAR.

The following Papers were read:—

I. "On a Compensated Air Thermometer." By H. L. CALLENDAR, M.A., Fellow of Trinity College, Cambridge. Communicated by Professor J. J. THOMSON, F.R.S. Received October 29, 1891.

In a paper which I had the honour to present to the Royal Society some four years ago "On the Practical Measurement of Tempera-

ture," * I described in detail a somewhat elaborate form of air thermometer with which it was found possible to attain an accuracy of the order of 0·01° C. I have since succeeded in overcoming some of the difficulties encountered in that investigation, and in evolving on similar lines a form of instrument which is capable of a much higher order of accuracy, and which has the further advantage that both the observations and the calculations are immensely simplified.

The standard instrument for measuring temperature selected by Regnault in his classical researches was the constant-volume air thermometer. In my earlier experiments I employed air thermometers of this type, but modified them by the introduction of a sulphuric acid gauge of small bore between the thermometric bulb and the mercury manometer. I was thus enabled to reduce the correction to be applied for the small volume of air which was not exposed to the temperature to be measured, and at the same time to observe small variations of temperature with greater accuracy.

The constant-volume type of air thermometer, however, has several disadvantages. The degree of accuracy attainable depends primarily on the exact measurement of pressure by means of a mercury manometer. The observations involved are slow and laborious, and it is difficult, unless the temperature is absolutely steady, to secure an accuracy of the order of a tenth of a degree C. At high temperatures this method has the further disadvantage that the bulb is exposed to variations of pressure, the effect of which in altering its volume cannot be accurately estimated.

For these and other reasons I soon abandoned the constant-volume air thermometer in favour of the constant-pressure type. The bulb may thus be entirely freed from stress at high temperatures, and the mercury manometer may be dispensed with. The auxiliary reservoir containing mercury into which the air is allowed to dilate may be kept permanently in melting ice, and the volume representing the dilatation of the air may be determined by weighing the mercury displaced. This observation may be made at leisure, and admits of very considerable accuracy.

With the form of instrument described in the previous paper, it was still necessary to read the barometer. These readings were found to be by far the greatest source of uncertainty. I was so much impressed with this in the course of some experiments on the boiling-point of sulphur† that I determined to construct an instrument which should be altogether independent of the measurement of mercury columns.

If the pressure of the air enclosed, instead of being adjusted to equality with that of the atmosphere, be adjusted always to the same

* 'Phil. Trans.,' A, 1887.

† 'Phil. Trans.,' A, 1891, p. 130.

standard constant pressure, the trouble of reading the barometer will be saved, and the calculations will be considerably simplified. The simplest, and at the same time the most accurate, method of securing a standard constant pressure is to connect the outer limb of the sulphuric acid gauge to a glass bulb filled with air of suitable density, and kept in melting ice, preferably in the same receptacle as the mercury bulb in which the dilatation of the air is measured. The pressure in the thermometric bulb can easily be adjusted to equality with the standard pressure to within 1 or 2 mm. of sulphuric acid, and the small outstanding difference of pressure can be read quickly and accurately by means of a kathetometer microscope.

I set up an experimental instrument of this kind in October, 1890, and satisfied myself that it was quite possible to read its indications to the thousandth part of a degree C. at ordinary temperatures. This, I believe, to be a very much higher order of accuracy than has hitherto been thought attainable with an air thermometer. My only remaining difficulty was the slight uncertainty as to the mean temperature of the connecting tubes. By the use of the sulphuric acid gauge it is possible to make this correction comparatively small, but it still remains uncertain, and varies slightly with the extent of immersion of the stem of the thermometer. It is also a rather troublesome correction to apply, and complicates all the calculations very considerably.

It has since occurred to me that this troublesome and uncertain correction may be entirely eliminated, both from the observations and from the calculations, with this particular form of instrument, by making the standard pressure bulb communicate with a set of connecting tubes equal in volume and similarly situated to those of the thermometric bulb itself.

The method of determining the correction to be applied for that part of the stem of which the temperature is variable, by means of a similar compensating tube placed in close proximity to it, has occasionally been applied by previous observers. It was first employed by Deville and Troost in 1864, in their experiments on the expansion of porcelain at high temperatures. They connected the compensating tube to a separate manometer, and by observing the pressure or the amount of the air it contained were enabled to eliminate the term representing the effect of the connecting tubes from their equations.

Other observers have used a similar device, but, so far as I am aware, no one has hitherto noticed that, in the case of the differential air thermometer, the compensation can be rendered automatic, so that changes of temperature of the connecting tubes have no effect on the readings, and need not be taken into account in the calculations.

The conditions under which the compensation is perfect with the

form of instrument above described are very simple. They are, (1) that the two sets of connecting tubes should be of equal volume and at the same mean temperature; (2) that the mass of air enclosed in the standard pressure bulb should be equal to that in the thermometric and mercury bulbs; (3) that the pressures should be adjusted to equality.

Let m_0 be the mass of air in the standard pressure bulb and its connecting tubes, and let p_0 be its pressure. Let V_0 be the volume of the bulb, and θ_0 its temperature measured on the scale of the air thermometer. Let v be the volume of the connecting tubes, and θ' their mean temperature; then we have

$$p_0\{V_0/\theta_0+v/\theta'\} = m_0k,$$

where k is a constant.

Let m_1 be the mass of air in the thermometric and mercury bulbs and their connecting tubes, and let p_1 be its pressure. Let V_1, V_m be the volumes of the air in these bulbs respectively at the temperatures θ_1 and θ_m; then we have as before

$$p_1\{V_1/\theta_1+V_m/\theta_m+v/\theta'\} = m_1k.$$

If now we make $m_0 = m_1$, and $p_0 = p_1$, we have the equation

$$V_0/\theta_0+v/\theta' = V_1/\theta_1+V_m/\theta_m+v/\theta'.$$

The term v/θ' disappears from the equation, and if we also make $\theta_0 = \theta_m$ by keeping both the mercury and standard pressure bulbs in melting ice, the value of θ_1 is *accurately* given by the very simple expression

$$\theta_1 = V_1\theta_0/(V_0-V_m).$$

It is convenient, and at the same time more symmetrical, to make the volume of the standard pressure bulb adjustable with mercury. It is then possible to take observations with the same thermometer at different pressures. By this means, as explained in a previous paper,* we can investigate with some accuracy the behaviour of gases at high temperatures, and thus reduce the indications of the air thermometer to the true scale of absolute temperature.

The form of instrument above described is designed for the most accurate work. For rough purposes, and especially for small ranges of temperature, very much simpler instruments may be constructed on similar principles.

It is evident, from an inspection of the equations already given, that the compensation is still sufficiently accurate for rough work, provided that the difference of pressure is small, and that the volume

* 'Phil. Trans.,' A, 1887, p. 223.

of the connecting tubes is not too large compared with that of the bulb. It is often a matter of great convenience to have the thermometric bulb at some distance from the indicating apparatus, and not rigidly connected to it. Since the connecting tubes are compensated, they may be made of considerable length and of flexible material, such as compo. or even rubber tubing, without much loss of accuracy.

For moderate ranges of temperature, an auxiliary bulb for measuring the dilatation of the air and adjusting the pressures to equality may be dispensed with. The sulphuric acid gauge itself may be graduated to indicate the difference of temperature between the two bulbs. In ordinary work, however, it would be inconvenient either to keep the standard bulb always at the same temperature, or to take its temperature and do an addition sum at each observation. The simplest way of avoiding this is to adjust the volume of the sulphuric acid in the pressure gauge so that its expansion may compensate for the dilatation of the air in the standard pressure bulb. This compensation may readily be made sufficiently accurate over the small range of temperature of the air of a workshop or laboratory.

When the instrument is thus compensated for changes of temperature in the standard bulb, one tube of the pressure gauge can be graduated directly in degrees to indicate the temperature of the thermometric bulb. The indications are then as easy to read as those of a mercury thermometer. They are not affected by changes of temperature in the surrounding air or by variations in the height of the barometer, and they are independent of the length of stem immersed. The range covered by a single instrument may be 100° C. or more, and may be made to correspond to any part of the scale by suitably adjusting the volumes of the air bulbs and tubes of the pressure gauge.

I have found such thermometers* exceedingly convenient and satisfactory for rough work at temperatures beyond the range of mercury thermometers. They can be made to read easily to the tenth of a degree at 450° C., and if properly compensated their indications are very reliable. Such a degree of accuracy is amply sufficient for most purposes, and the absence of all necessity for calculation or correction of the readings is a very great advantage.

* Perhaps I ought to mention that this direct-reading form of instrument has been patented, owing to its many commercial applications. It is made by Mr. J. J. Hicks, of Hatton Garden, E.C.